

6. REFERENCES

- Bahar E., and J.R. Wait (1965), Propagation in a model terrestrial waveguide of non-uniform height: theory and experiment, *J. Res. NBS* 69D, V No. 11, November, 1445-1463.
- Bean, B.R. (1979), Comment on evaluation of evaporation from Lake Ontario during IFYGL by a modified mass transfer equation, *Water Resources Research* 15, No. 3, 731.
- Bean, B.R. and B.A. Cahoon (1961), Limitations of radiosonde punch-card records for radiometeorological studies, *J. of Geophysical Res.* 66, No. 1, January, 328-331.
- Bean, B.R., B.A. Cahoon, C.A. Samson, and G.D. Thayer (1966), A world atlas of atmospheric radio refractivity, ESSA Monograph 1, NTIS Access No. AD-648-805.*
- Bean, B.R., and E.J. Dutton (1961), Concerning radiosondes, lag constants, and radio refractive index profiles, *J. of Geophysical Res.* 66, No. 11, November, 3717-3722,
- Bean, B.R., R.E. McGavin, R.B. Chadwick, and B.D. Warner (1971), Preliminary results of utilizing the high resolution FM radar as a boundary-layer probe, *Boundary Layer Meteorology* 1, 446-473.
- Cahoon, B.A., and L.P. Riggs (1964), Climatology of elevated superrefractive layers arising from atmospheric subsidence, *Proc. World Conference of Radio Meteorology*, Boulder, CO. (American Met. Soc., Boston, MA).
- CCIR (1978a), Report 715, Propagation by diffraction.**
- CCIR (1978b), Report 238-3, Propagation data required for trans-horizon radio-relay systems.**
- CCIR (1978c), Report 724, Propagation data for the evaluation of coordination distance in the frequency range 1 to 40 GHz.**
- CCIR (1978d), Recommendation 525, Calculation of free-space attenuation.**
- CCIR (1978e), Report 719, Attenuation by atmospheric gases.**
- CCIR (1978f), Report 718, Effects of tropospheric refraction of radiowave propagation.**
- CCIR (1978g), Annex of Recommendation 370-3, VHF and UHF Propagation curves for the frequency range from 30 MHz to 1000 MHz.**
- CCIR (1978h), Report 569-1, The evaluation of propagation factors in interference problems at frequencies greater than 0.6 GHz.**
- Cho, S.H., and J. R. Wait (1978), EM wave propagation in a laterally non-uniform troposphere, *Radio Science* 13, No. 2, March-April, 253.

* National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161.

** Vol. V., Propagation in Non-Ionized Media, CCIR XIV Plenary Assembly, Kyoto, Japan. Available from NTIS*, Access. No. PB 298-025/PG.

- Cho, S.H., C.G. Migliora, and L.B. Felsen (1979), Hybrid ray-mode formulation of propagation in a tropospheric duct, Session F-6, Proc. URSI/USNC Nat'l Radio Science Mtg., U. of Washington, Seattle, Wash., 18-22 June.
- Crane R.K.(1981), A review of transhorizon propagation phenomena, to appear in the March-April issue of Radio Science.
- Dougherty, H.T. (1968), A survey of microwave fading mechanisms, remedies, and applications, ESSA Tech. Report ERL 69-WPL4, NTIS Access Number COM-71-50288.*
- Dougherty, H.T., and B.A. Hart (1976), Anomalous propagation and interference fields, Office of Telecommunications Report 76-107, NTIS Access No. PB-262-477.*
- Dougherty, H.T., and B.A. Hart (1979), Recent progress in duct propagation predictions, IEEE Trans. Ant. Prop. AP-27, No. 4, July, 542-548.
- Dougherty, H.T., and W.J. Hartman (1977), Performance of a 400 Mbit/s system over a line-of-sight path, IEEE Trans. Comm. COM-25, No. 4, April, 427-432.
- Dougherty, H.T., R.E. McGavin, and R.W. Krinks (1970), An experimental study of atmospheric conditions conducive to high radio fields, Office of Telecommunications Report OT/ITSRR4, (available from NTIS under Access No. COM-75-11138/AS).*
- Dougherty, H.T., L.P. Riggs, and W.B. Sweezy (1967), Characteristics of the Atlantic Trade Wind System significant for radio propagation, ESSA Tech. Report IER 29-ITSA29, (NTIS Access No. AD-651-541).*
- Gossard, E.E. (1962), The reflection of microwaves by a refractive layer perturbed by waves, IRE Trans. AP-10, No. 3, May, 317-325.
- Gossard, E.E., and J.H. Richter (1970), The shape of internal waves of finite amplitude from high-resolution radar sounding of the lower atmosphere, J. Atmospheric Sciences 27, No. 6, Sept., 971-973.
- Gough, M.W. (1962), Propagation influence in microwave link operation, Institute of Radio Engineers (U.K.) 24, July, 53-72.
- Hall, F.F., Jr. (1971), Acoustic remote sensing of temperature and velocity structure in the atmosphere, Statistical Methods and Instrumentation in Geophysics, A.G. Kjelaas (Ed.), Oslo, Sweden: Teknologisk Forlag A/S.
- Hall, M.P.M. (1968), Further evidence of VHF propagation by successive reflections from an elevated layer in the troposphere, Proc. IEE 115, No. 11, 1595-1596.
- Hall, M.P.M. (1980), Effects of the Troposphere on Radio Communications, IEE Electromagnetic Waves Series, #8, Peter Peregrinus LTD, Stevenage, UK.
- Hall, M.P.M., and C.M. Comer (1969), Statistics of tropospheric radio refractive-index soundings taken over a three-year period in the United Kingdom, Proc. IEE 116, No. 5, May, 685-690.
- ITU (1976), Radio Regulations, Vols. I and II, (ISBN 92-61-00181-5), International Telecommunication Union, Geneva, Switzerland.

* National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161.

ITU (1979), Final Acts of the World Administrative Radio Conference, Vols. I and II, International Telecommunications Union, Geneva, Switzerland.

Kerr, D.E. (1951), Propagation of short radio waves, Chap. 1, Radiation Laboratory Series, Vol. 13 (McGraw Hill Book Company, Inc., New York, NY). Also available in paperback (Dover, Inc., New York, NY).

Majumdar, S.C., S.K. Sarkar, and A.P. Mitra (1977), Atlas of tropospheric radio refractivity over the Indian sub-continent, National Physical Laboratory, New Delhi, India.

Migliora, C.G., S.H. Cho, and L.B. Felson (1980), Hybrid ray-mode analysis of propagation in an elevated tropospheric duct, Proc. URSI Comm. F Open Symposium, Lennoxville, Quebec, 761-7.

Millington, G. (1957), The concept of the constant radius of the earth in tropospheric propagation, Marconi Rev. 20, No. 126, 79-93.

Neesen, J., and J. deHaas (1980), Measured statistics of transmission loss due to ducting on transhorizon links at 6.4 and 7.4 GHz, Proc. URSI-F Symposium, Quebec, Canada.

NTIA (1979), Manual of Regulations and Procedures for Federal Radio Frequency Management, U.S. Dept of Comm., National Telecommunications and Information Administration, 1325 G. St. N.W., Wash., DC 20005.

Ott, R.H. (1980), Roots of the modal equation for EM wave propagation in a tropospheric duct, J. of Math. Physics 21, No. 5, May, 1256-1266.

Richter, J.H. (1969), High resolution tropospheric radar sounding, Radio Sci. 4, No. 12, December, 1261-1268.

Samson, C.A. (1975), Refractivity gradients in the northern hemisphere, Office of Telecommunications Report 75-59, NTIS Access No. COM-75-10776/AS.*

Saxton, J.A. (1951), The propagation of meteorological waves beyond the horizon, Proc. IEE, 98, Pt. III, 360-369.

Segal, B., and R.E. Barrington (1977), Tropospheric refractivity atlas for Canada, CRC Report 1315, Dept. of Communications, Ottawa, Canada.

Wait, J.R. (1962), Electromagnetic waves in stratified media, Chaps. XI and XII (Pergamon Press, New York, NY). There is also a second edition, 1970.

Wait, J.R. (1964), A note on the VHF reflection from a tropospheric layer, Radio Sci. 68D, No. 7. July, 847-848.

Wait, J.R. (1969), Reflection from subrefractive layers, Electronic Letters 5, No. 4, February 20, 64-65.

Wait, J.R., and K.P. Spies (1969), Internal guiding of microwaves by an elevated tropospheric layer, Radio Sci. 4, No. 4, April, 319-326.

* National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161.

APPENDIX A: DUCTING EXPRESSIONS

Millington [1957] showed that a radio wave trajectory within a layer of constant refractivity gradient may be closely approximated by a parabolic arc. His results can be expressed as

$$y(x) = x\theta_0 + \frac{x^2}{2} G \quad \text{m,} \quad (\text{A1})$$

$$\theta(x) = \theta_0 + xG \quad \text{mrad,} \quad (\text{A2})$$

$$G = [g + 157] 10^{-3} \quad \text{M units/m.} \quad (\text{A3})$$

The $0 \leq y \leq \delta h$ of (A1) gives the height of a point on the wave trajectory in meters above the layer base elevation (h_0 in Figures 5 and 6) and at a distance of x kilometers from the origin ($y = 0$, $x = 0$). Note that (A1) is relative to the layer base, regardless of its shape; its shape may change as the layer is arched or flat, but the equation is unchanged. Equation (A2) determines the elevation angle along the wave trajectory in milliradians and is the derivative (with respect to x) of (A1) for the small-angle approximation $\theta(x) \approx \tan \theta(x)$. The layer's modified refractivity gradient $G = G_0 < 0$ M units/m would be determined by (A3) from the layer's ducting refractivity gradient $g_0 < -157$ N units/km. For that portion of the duct below the ducting layer, then $y(x) = h(x) - h_0 \leq 0$, where $h_b \leq h(x) \leq h_0$. The modified refractivity gradient $G = G_b > 0$ M units/m is also determined from (A3), but for a refractivity gradient $g_b > -157$ N units/km. Commonly,

$$G_b = [-40 + 157] 10^{-3} = 0.117 \quad \text{M units/m.} \quad (\text{A4})$$

By manipulation of (A1), (A2), and (A3), several of the trajectory characteristics may be determined. For example, the maximum take-off angle (at $x = 0$) for a trapped trajectory is known as the critical take-off angle

$$\theta_c = \pm \sqrt{2 |\delta M|} \quad \text{mrad,} \quad (\text{A5})$$

where the choice of sign is such as to maintain θ_c/G positive. In (A5),

$$\delta M = G_0 \delta h < 0 \quad \text{M units,} \quad (\text{A6})$$

and δh is the ducting-layer thickness in meters. The duct thickness is, from (6),

$$D = \delta h [1 - G_0/G_b] \quad \text{m.} \quad (\text{A7})$$

For an initial elevation angle θ_0 at $y = 0$, the wave trajectory parabolic arc within the layer will have, from (A2), a maximum elevation \hat{y} at

$$\hat{x} = -\theta_0/G_0 \quad \text{km,} \quad (\text{A8})$$

and

$$\hat{y} = \theta_0 \hat{x}/2 = -\theta_0^2/2G_0 \quad \text{m.} \quad (\text{A9})$$

Of course,

$$\frac{\hat{y}}{\delta h} = \left(\frac{\theta_0}{\theta_c} \right)^2 \leq 1.0 \quad (\text{A10})$$

At the point $y(x)$,

$$x = \hat{x} [1 \mp Q(x)] \quad \text{km,} \quad (\text{A11})$$

and

$$\theta(x) = \pm \theta_0 Q(x) \quad \text{mrad,} \quad (\text{A12})$$

where the choice of sign is the opposite of that for (A11). For example, $\theta(x) > 0$ for $x < \hat{x}$. The $Q(x)$ is given by

$$Q(x) = \sqrt{1-y(x)/\hat{y}} \quad \text{for } y > 0, \quad (\text{A13})$$

and

$$Q(x) = \sqrt{1-y(x)/\hat{y}_b} \quad \text{for } y < 0, \quad (\text{A14})$$

where

$$\hat{y}_b = \delta h \frac{G_0}{G_b} < 0 \quad \text{m.} \quad (\text{A15})$$

For the trajectory parabolic arc, $y(x) \geq 0$, the chord length from $y(x=0)$ to $y(x=x_{\max}) = 0$ is

$$(x_{\max})_0 = \hat{x}_b = -2\theta_0/G_0 > 0 \quad \text{km.} \quad (\text{A16})$$

For the trajectory parabolic arc $y(x) \leq 0$, the chord length is given by

$$(x_{\max})_b = - (x_{\max})_0 \frac{G_0}{G_b} > 0 \quad \text{km,} \quad (\text{A17a})$$

$$= \hat{x}_b = -2\theta_0/G_b > 0 \quad \text{km.} \quad (\text{A17b})$$